



# J/ $\psi$ and $\Upsilon$ measurements via di-lepton decay channels with the STAR experiment

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# Outline

- Quarkonia as a QGP Probe
- STAR experiment
- $J/\psi \rightarrow e^+ + e^-$ ,  $J/\psi \rightarrow \mu^+ + \mu^-$ 
  - $R_{AA}$
  - $v_2$
- $\Upsilon \rightarrow e^+ + e^-$ ,  $\Upsilon \rightarrow \mu^+ + \mu^-$ 
  - $R_{AA}$
- Conclusions and outlook

# Quarkonia as a QGP Probe

- Quarkonia suppression due to Debye screening proposed as a signature of QGP formation
  - Heavy quarks produced early in the collision
  - Interpreting observed suppression requires a variety of measurements

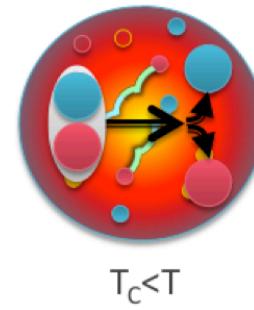
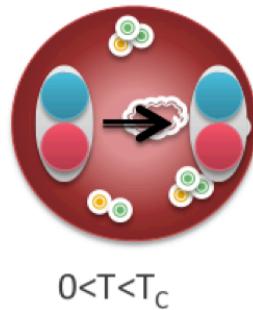
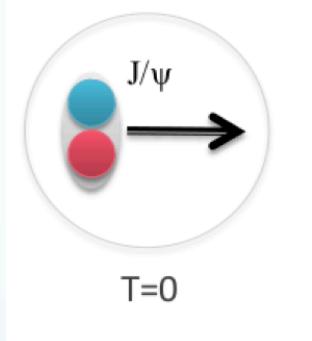
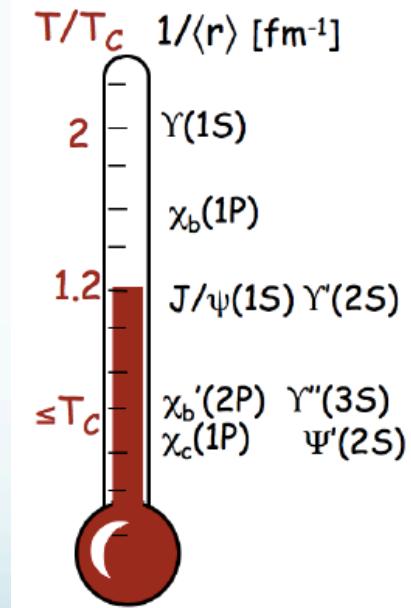


Illustration: A. Rothk

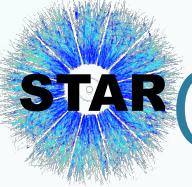
T. Matsui, H. Satz,  
Phys.Lett. B178, 416  
(1986)

- Different states dissociate at different temperatures Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)
  - Allows quarkonia to serve as a model dependent QGP thermometer



Á. Mocsy, EPJC61  
(2009) 705

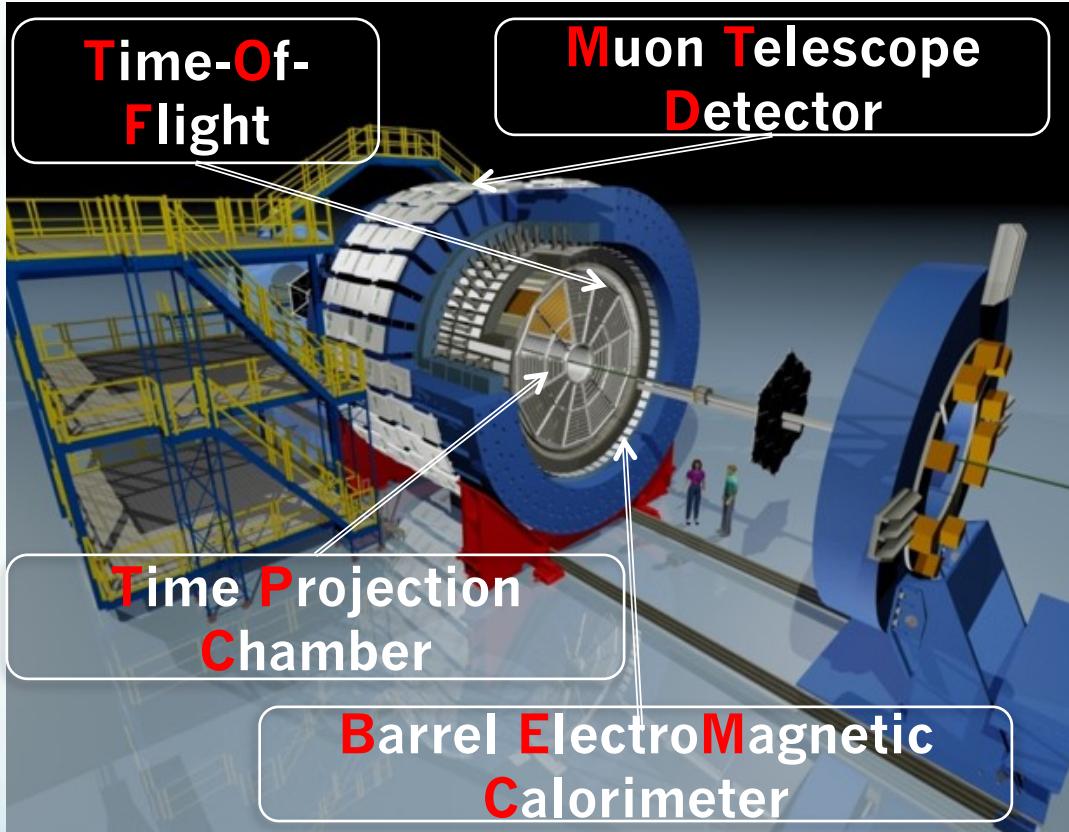
$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$



# Quarkonia measurements at STAR

- A wide variety of J/ $\psi$  measurements
  - Different energies → Change in relative contributions of color screening, recombination and CNM
  - Different species
    - d+Au → cold nuclear matter (CNM) effects
    - Au+Au, U+U → hot plasma effects, different energy densities
- $\Upsilon$  Measurements → Clean Probe at RHIC
  - Co-mover absorption and recombination is negligible
  - Small cross-section requires large statistics

# **STAR** Solenoid Tracker At RHIC (STAR)



Acceptance:  $|\eta| < 1, 0 < \phi < 2\pi$   
BBC/VPD used for MB trigger condition

- **TPC:** precise momentum and energy loss - PID
- **TOF:** measure time-of-flight - PID
- **BEMC:** electron trigger and PID
- **MTD:** muon trigger and PID
  - Installed behind magnet
  - Precise timing ( $\sigma \sim 100$  ps)

# J/ $\psi$ in p+p 200 GeV

- $0 < p_T \text{ J}/\psi < 14 \text{ GeV}/c$ 
  - Agrees well with PHENIX
    - STAR 2009 EMC : Phys. Lett. B 722 (2013) 55
    - STAR 2009 MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543
    - STAR 2005 & 2006: Phys. Rev. C80, 041902(R) (2009)
    - PHENIX 2006: Phys. Rev. D 85, 092004 (2012)
  - Baseline for Au+Au
  - Model comparisons:
    - Prompt NLO CS+CO
      - Describes  $p_T > 4 \text{ GeV}/c$  spectrum
    - Direct NNLO\* CS:
      - under-predicts high- $p_T$  spectrum
    - Prompt CEM:
      - Over predicts the data at  $p_T \sim 3 \text{ GeV}/c$

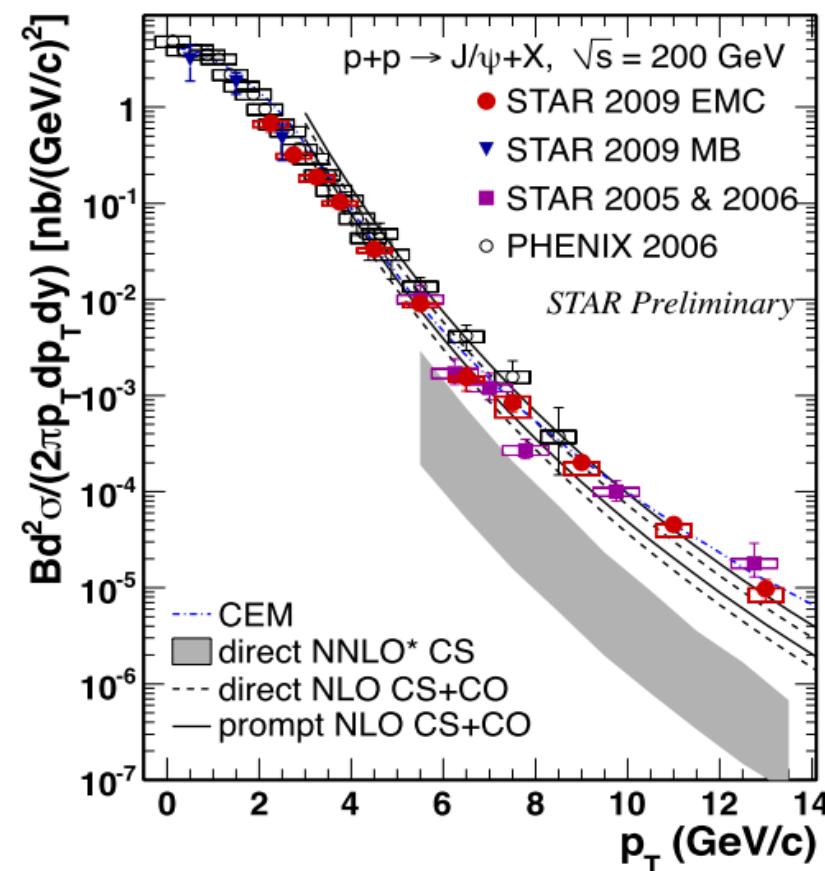
direct NNLO CS: P.Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008) and

J.P.Lansberg private communication

NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, Phys. Rev. D 84, 51 114001 (2011) and priv. comm.

CEM: A.D. Frawley, T.Ullrich, R.Vogt, Phys. Rept. 462 (2008) 125, and R.Vogt priv. comm.

## Inclusive J/ $\psi$ spectra:

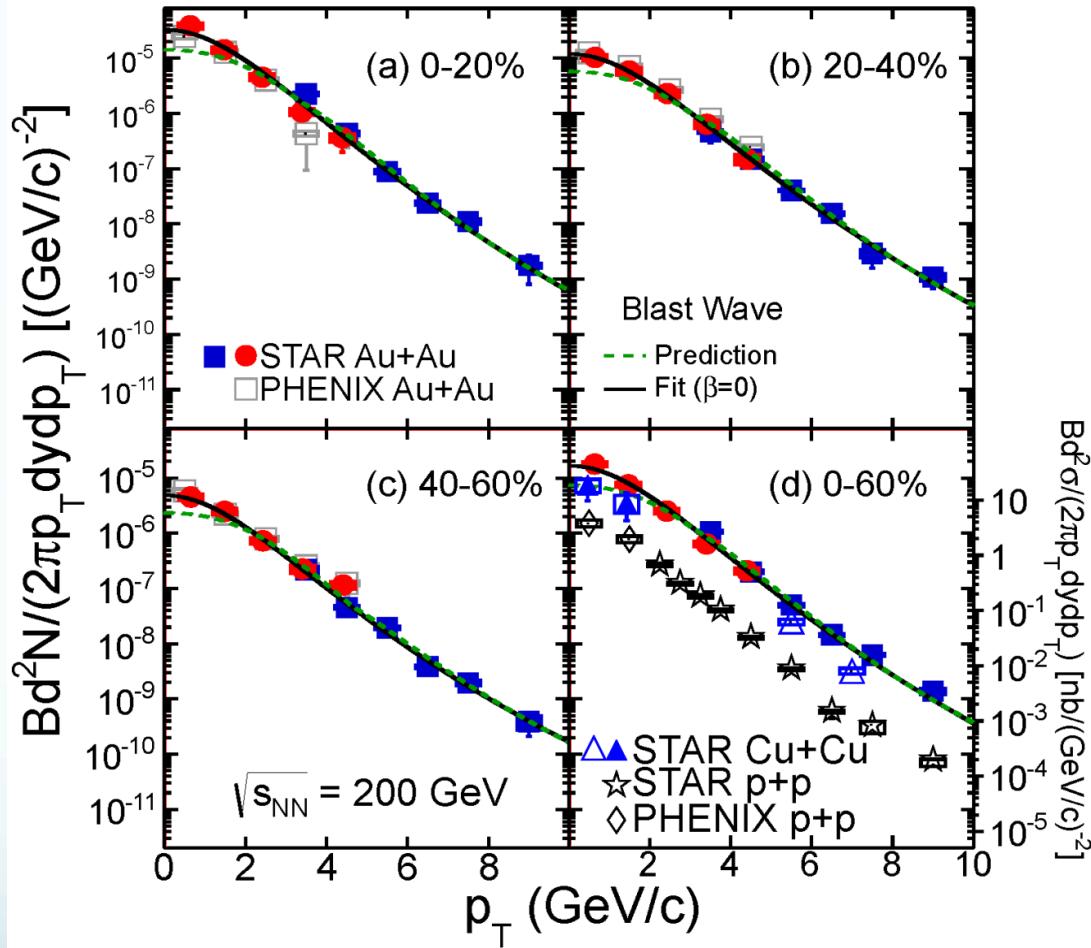


Difficulty to describe both yield and polarization of J/ $\psi$



# J/ $\psi$ in A+A at 200 GeV

- J/ $\psi$  spectrum softer than Tsallis Blast-Wave prediction
  - Small radial flow?
  - Recombination at low  $p_T$ ?
- Tsallis Blast-Wave:
  - Hydro-inspired freeze-out
  - Particles produced according to a Lévy-distribution



STAR low- $p_T$  Au+Au, Cu+Cu : Phys. Rev. C 90 (2014) 24906

high- $p_T$  Au+Au: Phys. Lett. B722, 55 (2013)

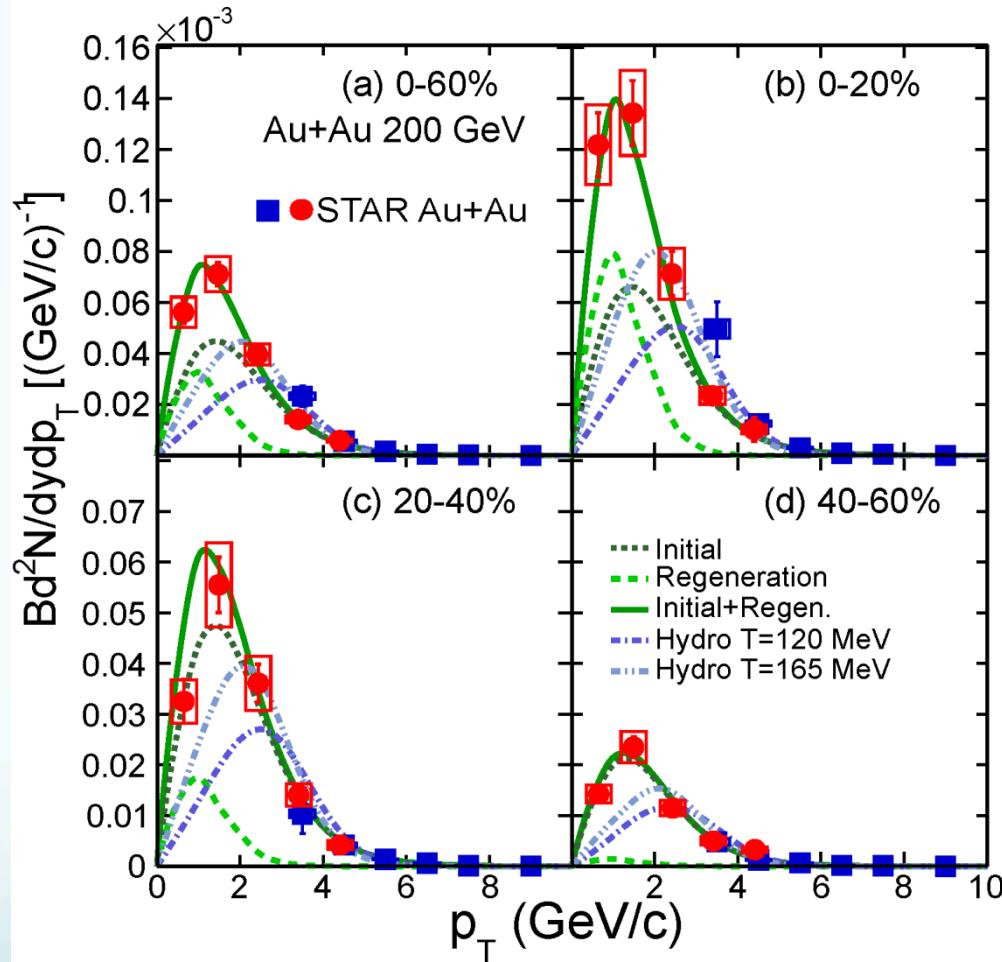
high- $p_T$  Cu+Cu : Phys. Rev. C 80 (2009) 041902

PHENIX: Phys. Rev. Lett. 98 (2007) 232301

Tsallis B-W: Z.Tang et al., Chin.Phys.Lett. 30, 031201 (2013)

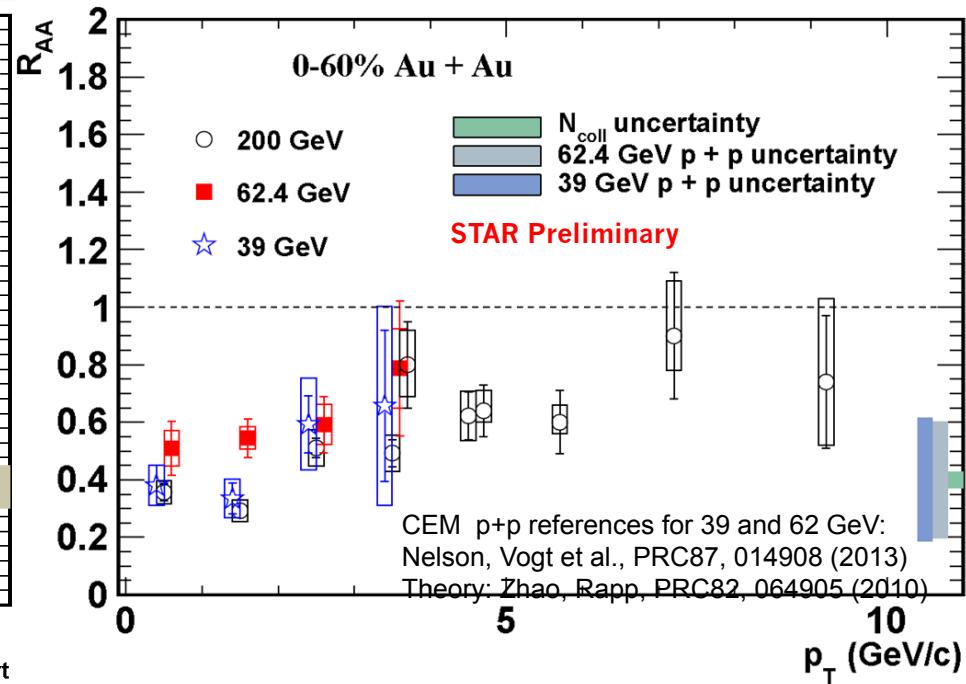
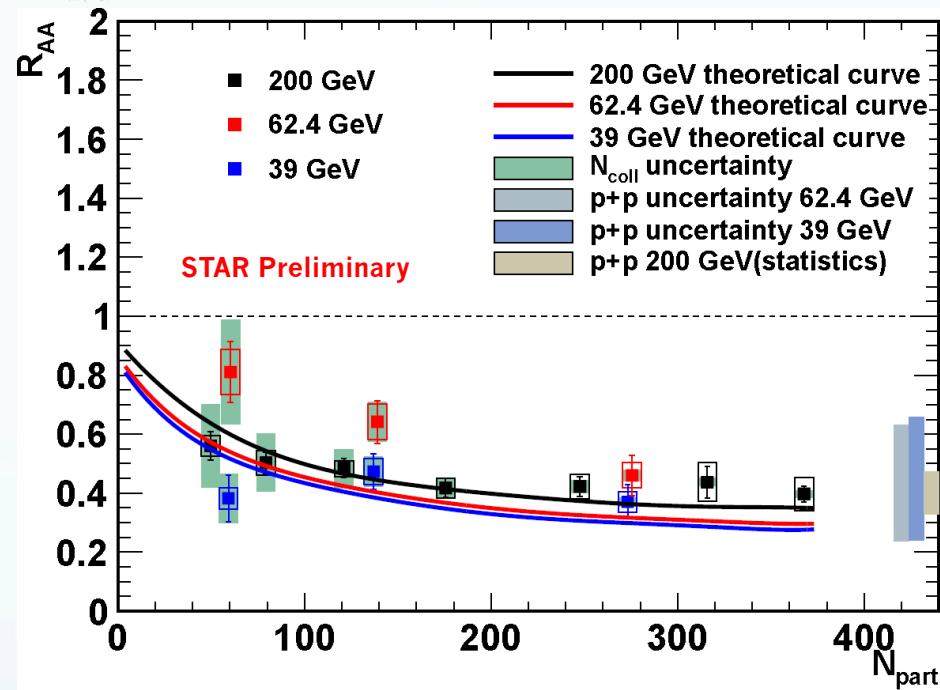
# J/ $\psi$ in Au+Au at 200 GeV

- Viscous hydrodynamics
  - J/ $\psi$  decouples at 120-165 MeV
  - Fails at low- $p_T$
- Y. Liu et al. includes J/ $\psi$  suppression due to color screening and statistical regeneration
  - Peripheral collisions: initial production dominates
  - Central collisions: regeneration becomes significant at low  $p_T$
- Charm quark coalescence is needed**



Y. Liu et al., Phys. Lett. B 678, 72 (2009)  
 U. W. Heinz and C. Shen (2011), private communication  
 STAR low- $p_T$  Au+Au, CuCu : Phys. Rev. C 90 (2014) 24906  
 high- $p_T$  Au+Au: Phys.Lett. B722, 55 (2013)

# J/ $\psi$ R<sub>AA</sub> vs. beam energy

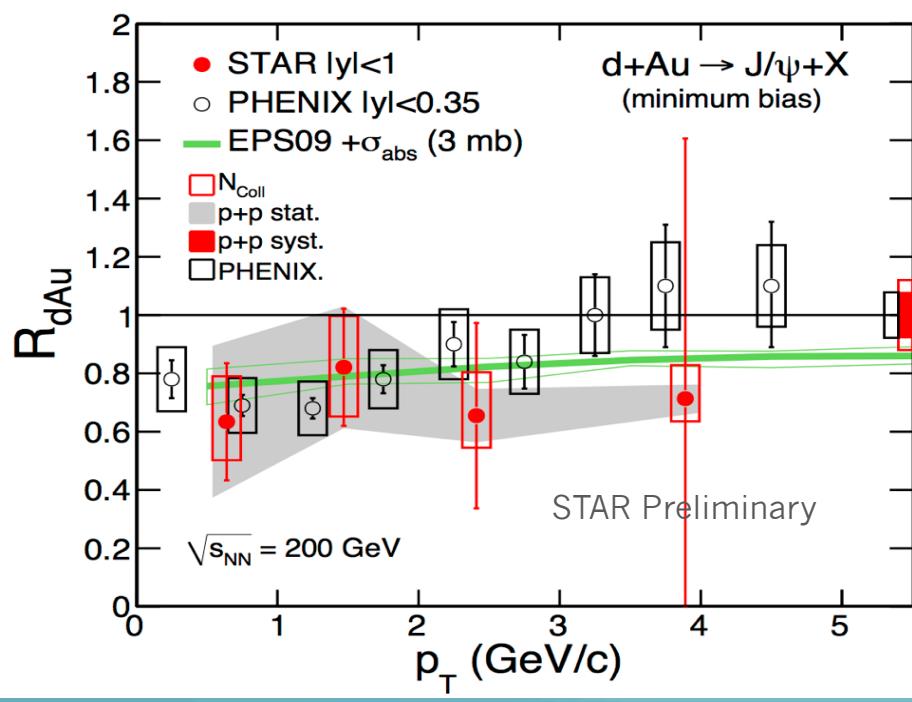


- Similar suppression at **200, 62.4, 39** GeV
  - p+p reference for 62.4 and 39 based on CEM calculations → large theoretical uncertainty
- Consistent with theoretical calculations
  - Does coalescence compensate for dissociation?

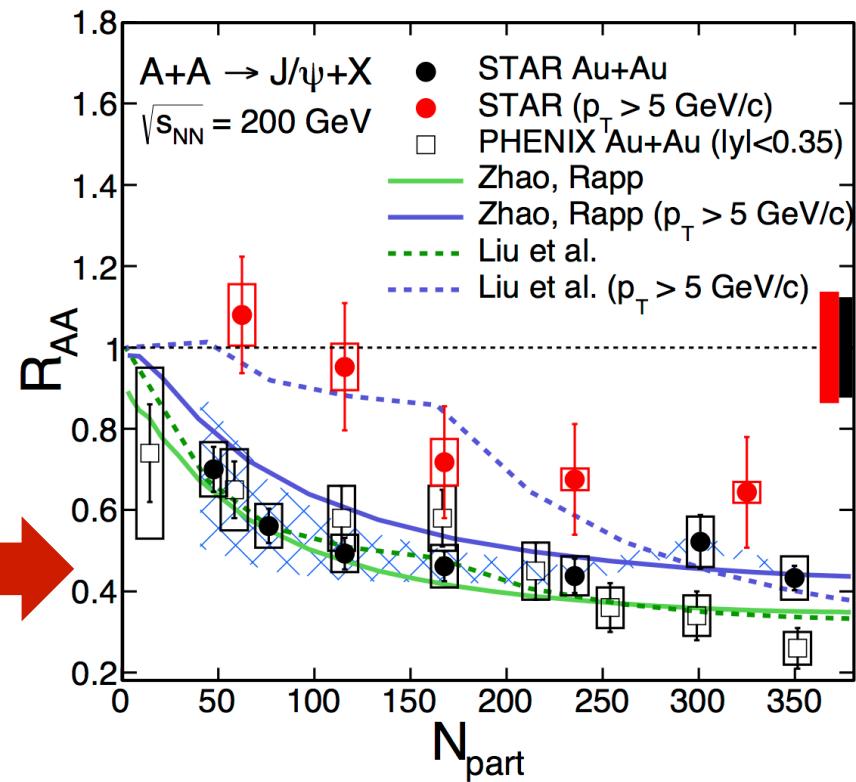
$$R_{AA} = \frac{\langle \sigma_{inel} \rangle}{\langle N_{coll} \rangle} \frac{\frac{d^2 N_{AA}}{dy dp_T}}{\frac{d^2 \sigma_{pp}}{dy dp_T}}$$

# High- $p_T$ J/ $\psi$

- d+Au → Allows quantification of cold nuclear matter effects
  - $R_{d\text{Au}} \approx 1$  for high  $p_T$  J/ $\psi$
  - **CNM effects are small at high- $p_T$**



- High- $p_T$  J/ $\psi$  is suppressed in central Au+Au collisions
  - Indicates that the **observed suppression is a QGP effect**





# Does J/ $\psi$ flow?

- Primordial J/ $\psi$ : little or zero  $v_2$
- Regenerated J/ $\psi$ : inherit  $v_2$  from the constituent charm quarks
- $p_T > 2 \text{ GeV}/c \rightarrow v_2 \text{ is consistent with zero}$ 
  - Contribution of regenerated J/ $\psi$  is small or constituent charm flow is small
    - $v_2$  disfavors scenario of J/ $\psi$  predominately produced from coalescence of charm quarks with the same  $v_2$  as the medium
  - Non-flow effects estimated using J/ $\psi$ -h correlations in pp collisions can account for possible deviation from zero at high  $p_T$

STAR, PRL 111 (2013) 052301

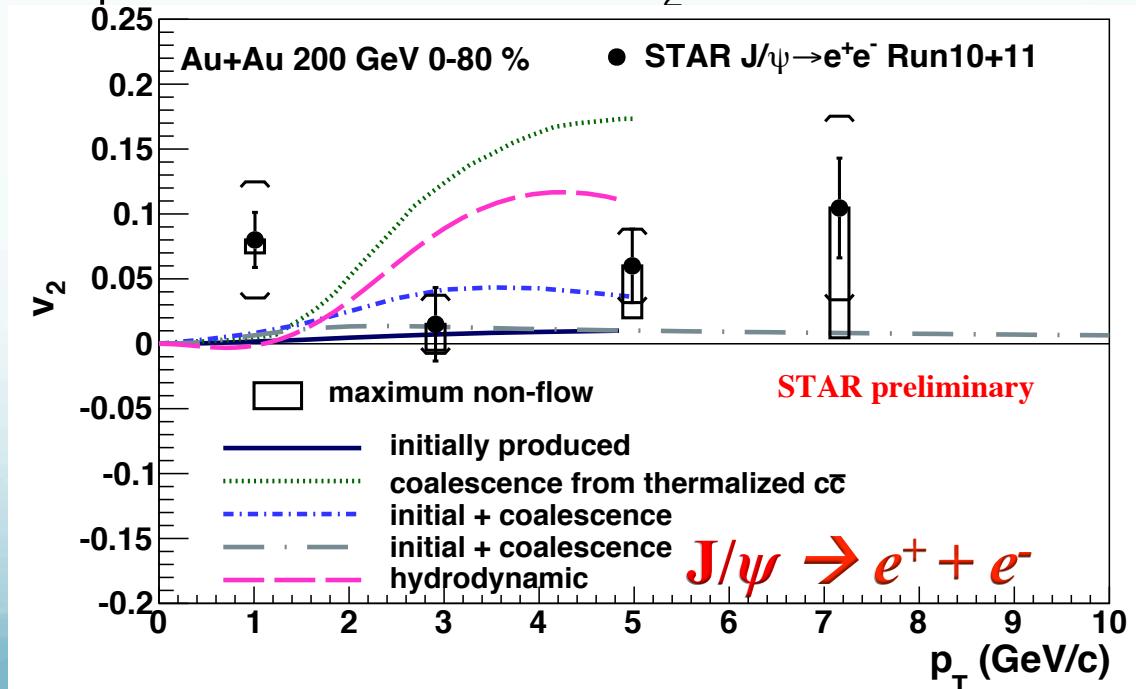
L. Yan, P. Zhuang, and N. Xu, PRL 97 (2006) 232301

V. Greco, C.M. Ko, and R. Rapp, PLB 595 (2004) 202

X. Zhao and R. Rapp, arXiv: 0806.1239

Y. Liu, N. Xu and P. Zhuang, NPA 834 (2010) 317

U.W. Heinz and C. Shen, (private communication)



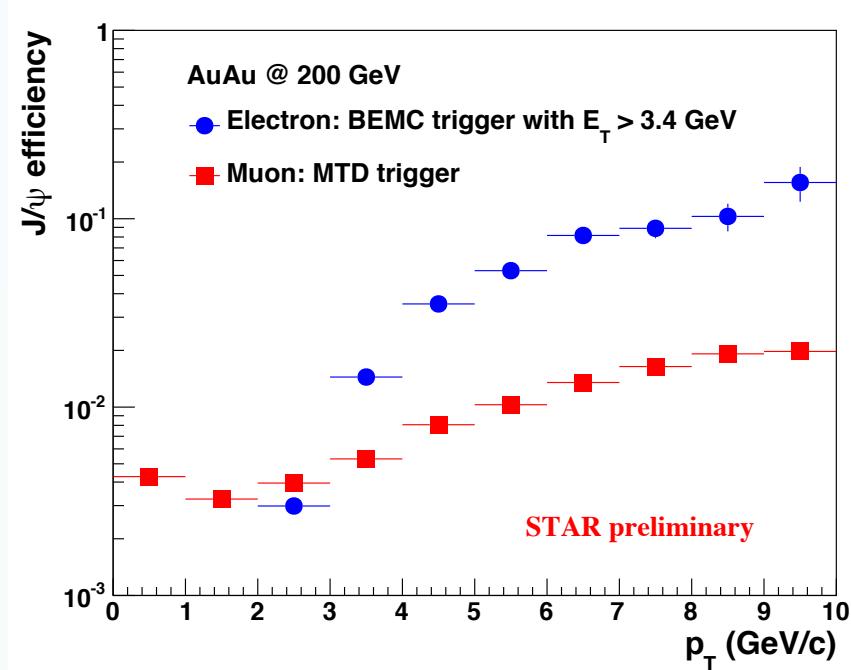
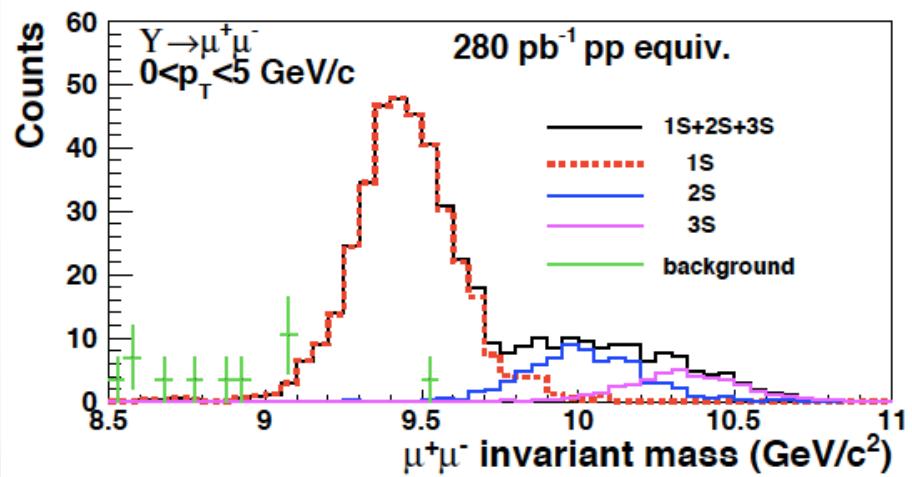


- Full installation of the Muon Telescope Detector (MTD) in 2014 allows quarkonium measurements in the dimuon channel!
- Dimuon trigger: two hits in MTD in the same bunch crossing
- Integrated luminosity  $\sim 14.2 \text{ nb}^{-1}$  of Au+Au collisions at 200 GeV recorded in 2014
  - Only 30% is used for the results presented here
  - Total integrated luminosity expected to be similar in 2016
- Muon identification cuts
  - Energy loss measurement by TPC
  - Match TPC tracks to MTD
    - Distance between MTD hits and projected TPC tracks along both z and  $\phi$  directions
    - Time difference between MTD measured time and expected travel time of muons



# Muon Telescope Detector (MTD)

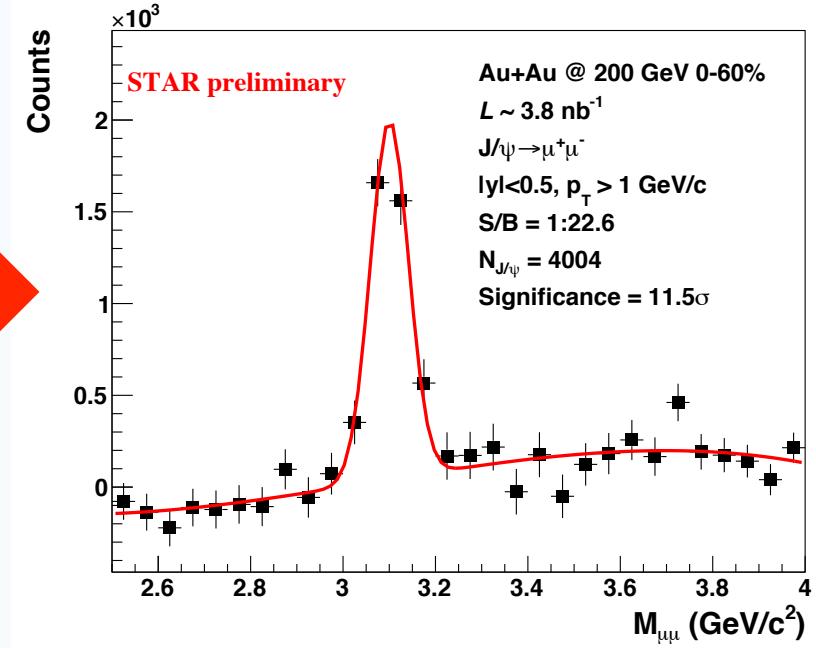
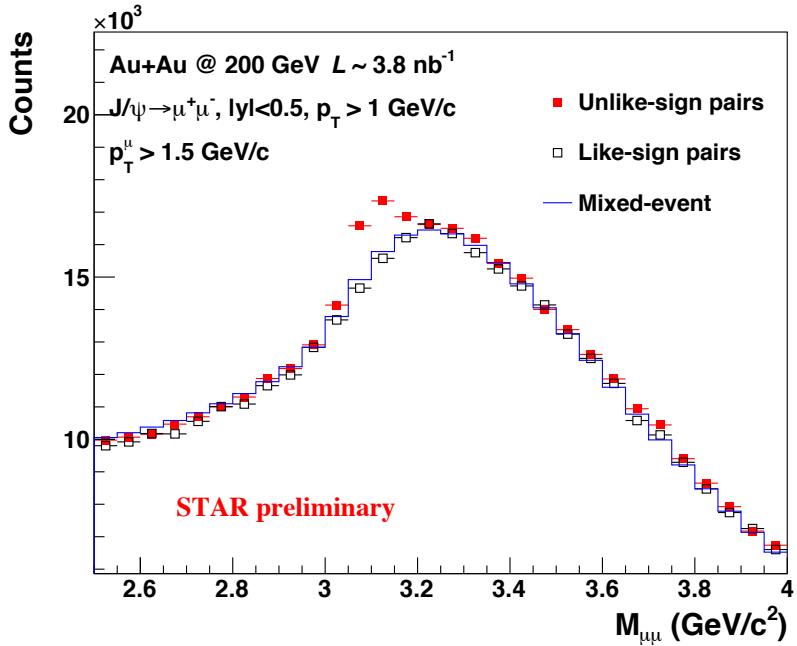
- Relatively high reconstruction efficiency for  $J/\psi$  at low  $p_T$ 
  - Covers a wide kinematic range



- MTD will allow us to separate  $\Upsilon(2S+3S)$  from  $\Upsilon(1S)$
- Potential to separate  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states as muons suffer less from bremsstrahlung than electrons



# J/ $\psi$ yield extraction

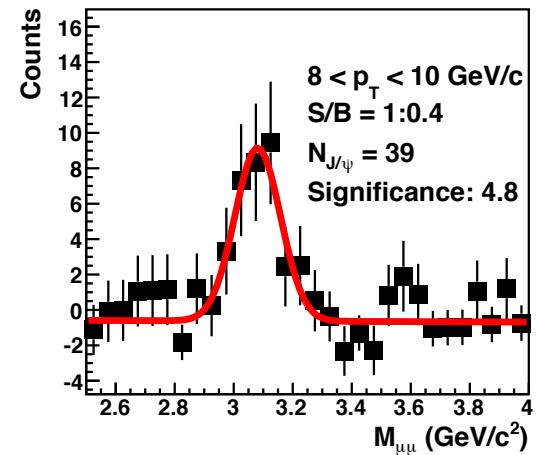
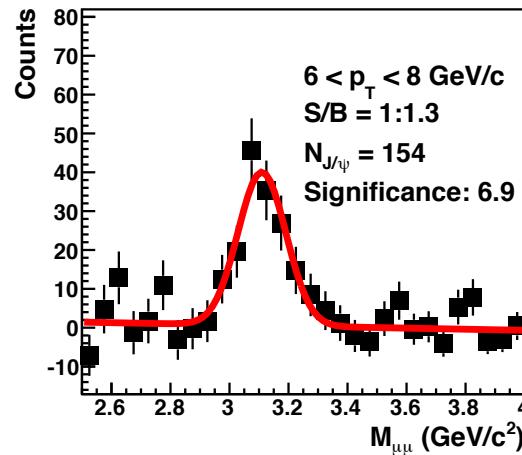
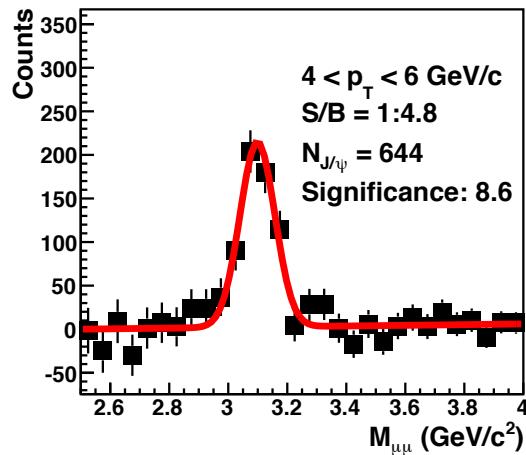
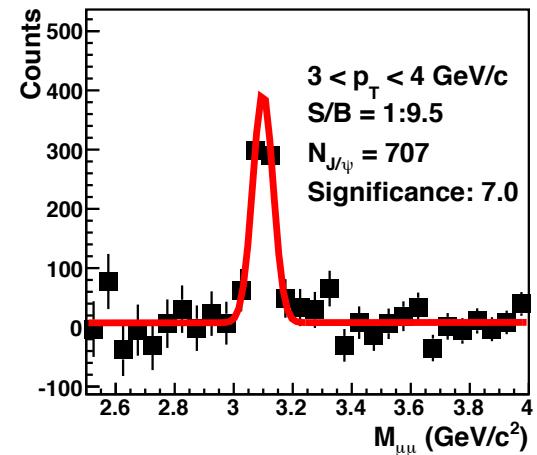
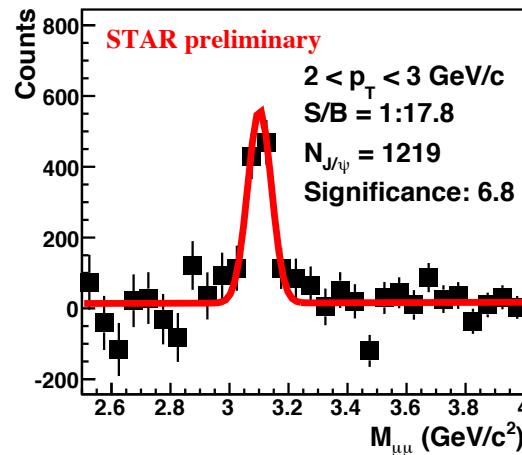
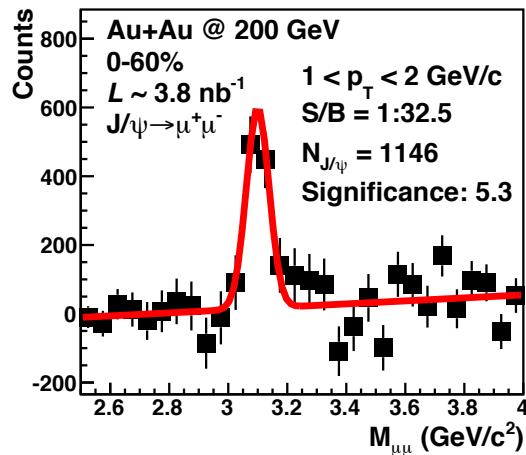


- Signal extraction
  - Mixed-event describes combinatorial background
  - Fit background-subtracted unlike-sign with Gaussian+3<sup>rd</sup> order polynomial
- Signal = (counts in [2.9,3.3]  $\text{GeV}/c^2$ ) – (residual background)

**No bremsstrahlung tail**  
S/B = 1:23  
 $N \sim 4000$   
 $\text{Sig} \sim 11.5\sigma$



# J/ $\psi$ versus $p_T$



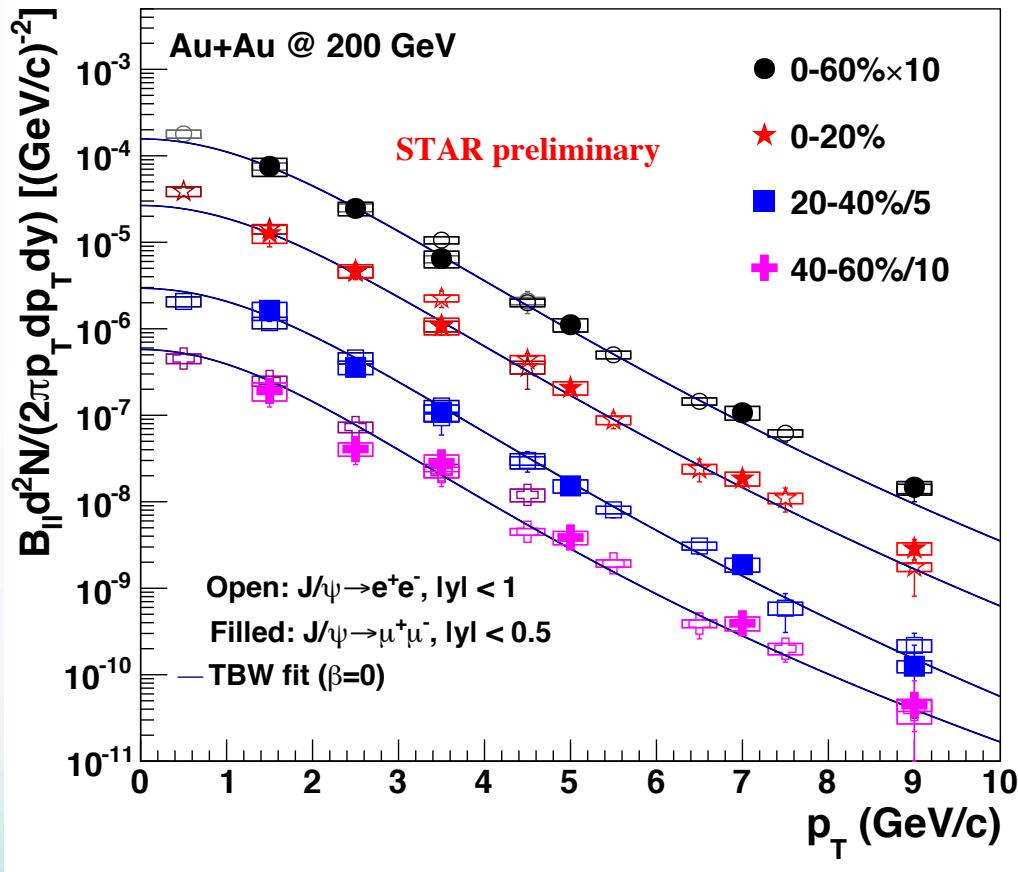
Increase in  $J/\psi$   $p_T$

- Increase S/B
- Wider  $J/\psi$  peak
- Fewer signal counts

Rosi Reed - High  $p_T$  Workshop

MTD covers a wide  $J/\psi$  kinematic range

# $J/\psi \rightarrow \mu^+ + \mu^-$ Yield



Di-electron:  
 STAR PLB 722 (2013) 55  
 STAR PRC 90, 024906 (2014)

- First mid-rapidity measurement of  $J/\psi \rightarrow \mu^+ + \mu^-$  yield in Au+Au collisions
  - $1 < p_T < 10$  GeV/c
- Consistent with the Run 10 published di-electron results over the entire kinematic range.

# $J/\psi$ $R_{AA}$

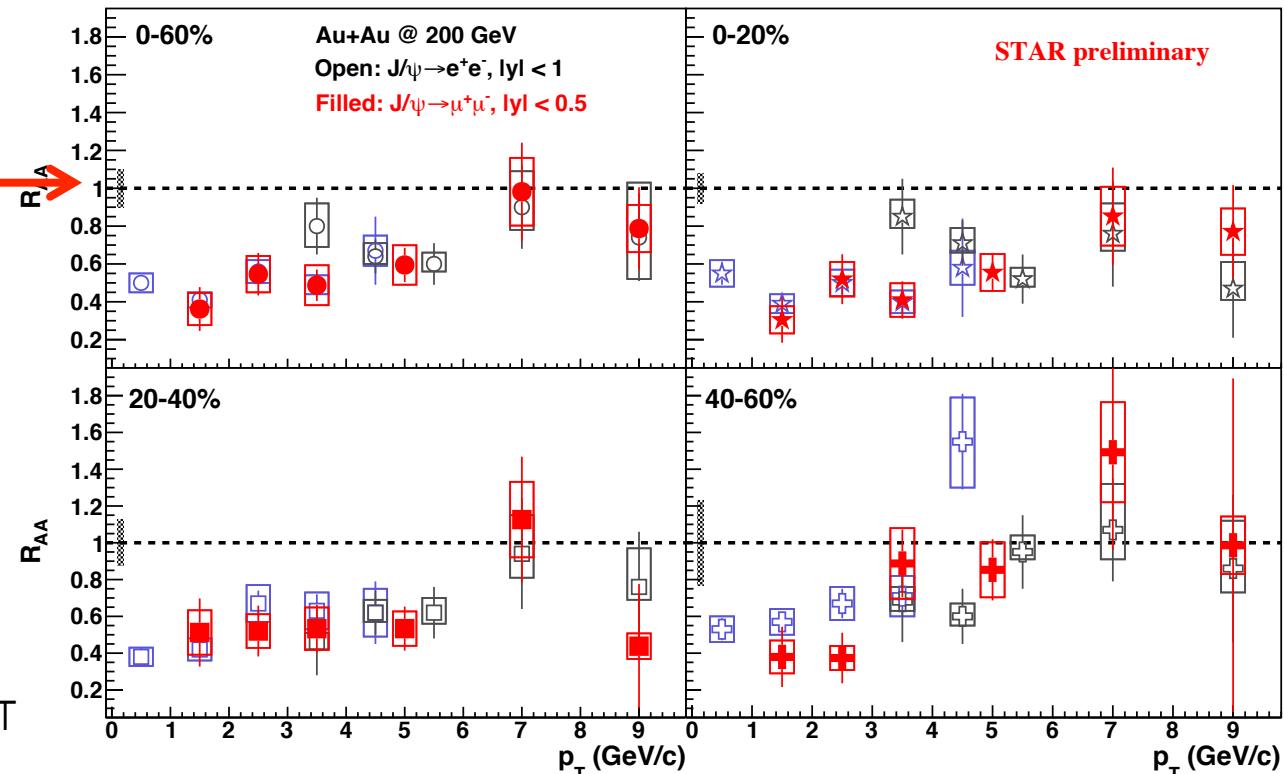
Scale uncertainty  
for  $\sigma_{inel}$  and  $N_{coll}$

Strong low  $p_T$   
suppression

- Dissociation
- CNM effects

Suppression  
decreases at high  $p_T$

- Dissociation
- Formation time effect
- Feed-down from B-hadrons

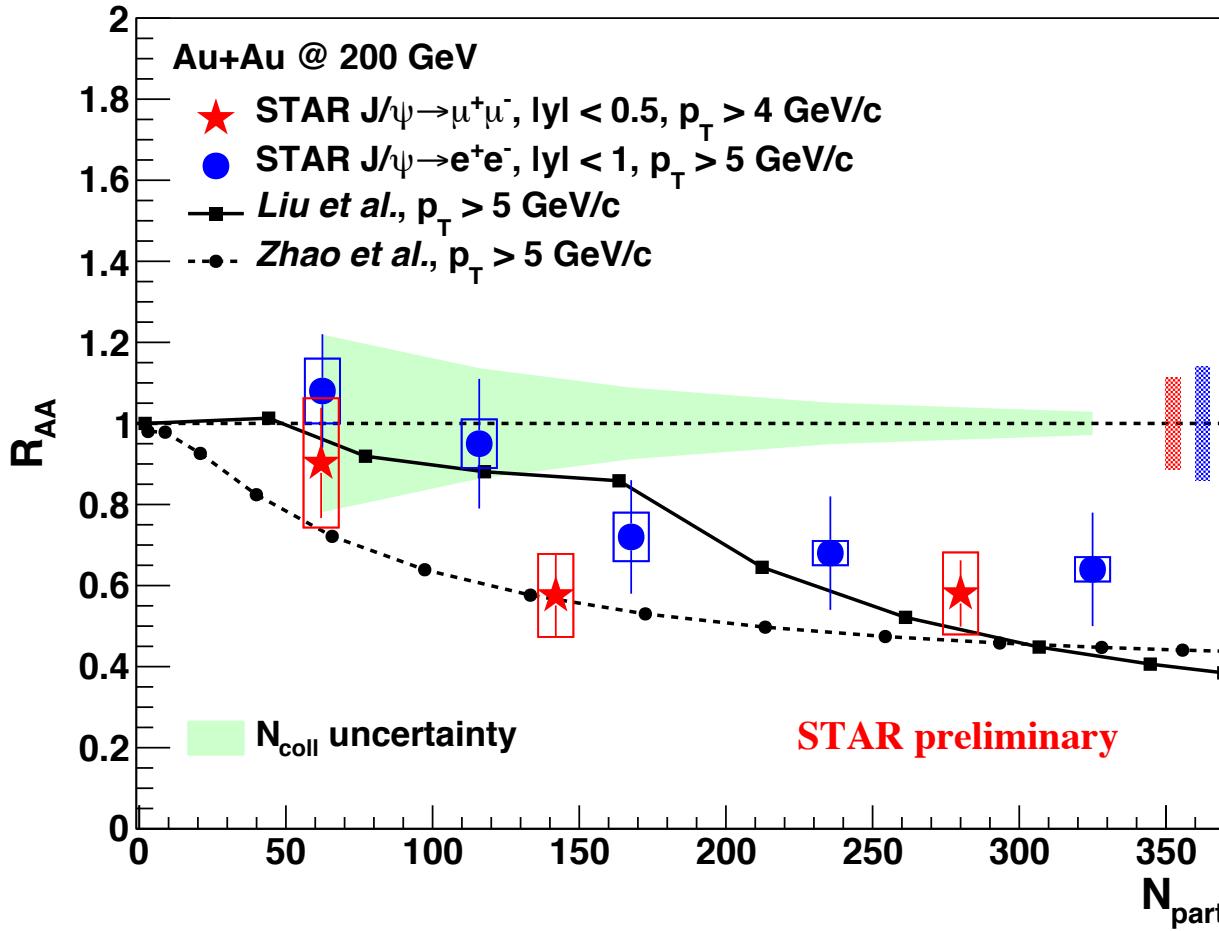


Di-electron:  
STAR PLB 722 (2013) 55  
STAR PRC 90, 024906 (2014)

Results confirm the **rising  $R_{AA}$  with  $p_T$**  seen with the  
di-electron channel



# J/ $\psi$ R<sub>AA</sub> vs N<sub>part</sub>



Significant J/ $\psi$  suppression with  $p_T > 4$  GeV/c

- Seen in both 0-20% and 20-40% centralities
- QGP effect → dissociation

STAR PLB 722 (2013) 55  
Y.-p. Liu, et al. PLB 678 (2009) 72  
X. Zhao et al. PRC 82 (2010) 064905



# J/ $\psi$ conclusions

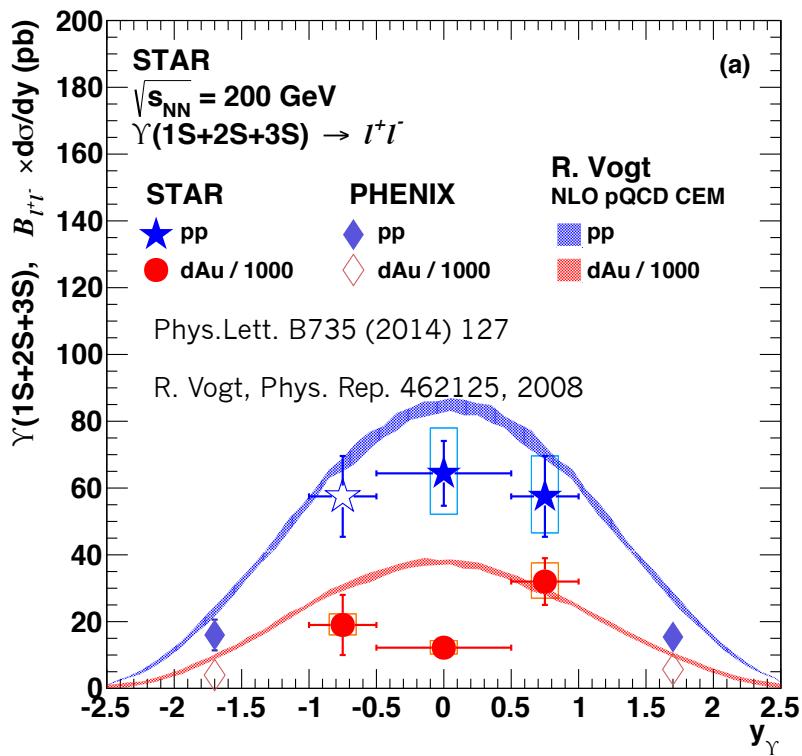
- $R_{AA} \rightarrow$  suppression  $\rightarrow$  similar for central 39, 62.4 and 200 GeV data
  - Indicates **regeneration plays a large role**
- Low  $p_T$  J/ $\psi$  not described by Tsallis Blast-Wave
  - Indicates **regeneration plays a large role**
- Significant suppression in central collisions for  $p_T > 4$  GeV/c
  - Dissociation  $\rightarrow$  not seen in d+Au  $\rightarrow$  **QGP effect**
- $R_{AA}$  rises with  $p_T$
- No strong  $v_2$  or radial flow observed for  $p_T > 2$  GeV/c
  - Updated J/ $\psi$   $v_2$  in di-electron channel combining Run 10 and Run 11 data
  - **Thermalized charm coalescence does not dominate J/ $\psi$  production for  $p_T > 2$  GeV**



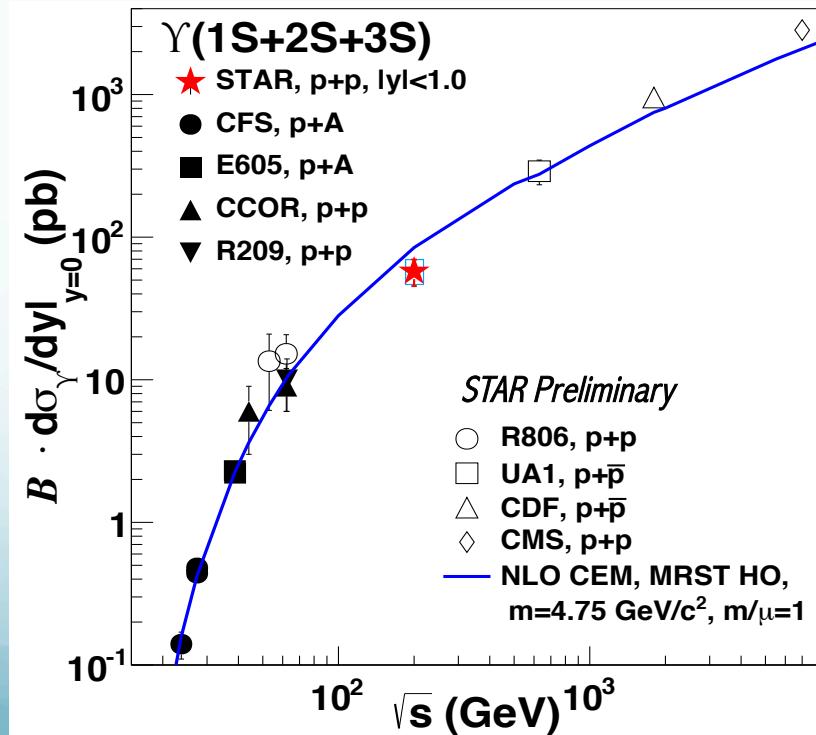
# $\Upsilon(1S+2S+3S)$ at STAR

- $\Upsilon$  advantages → background is small, and both co-mover absorption and recombination are negligible at RHIC energies
  - Disadvantage is the low cross-section
  - Good tracking resolution needed to separate 3 states

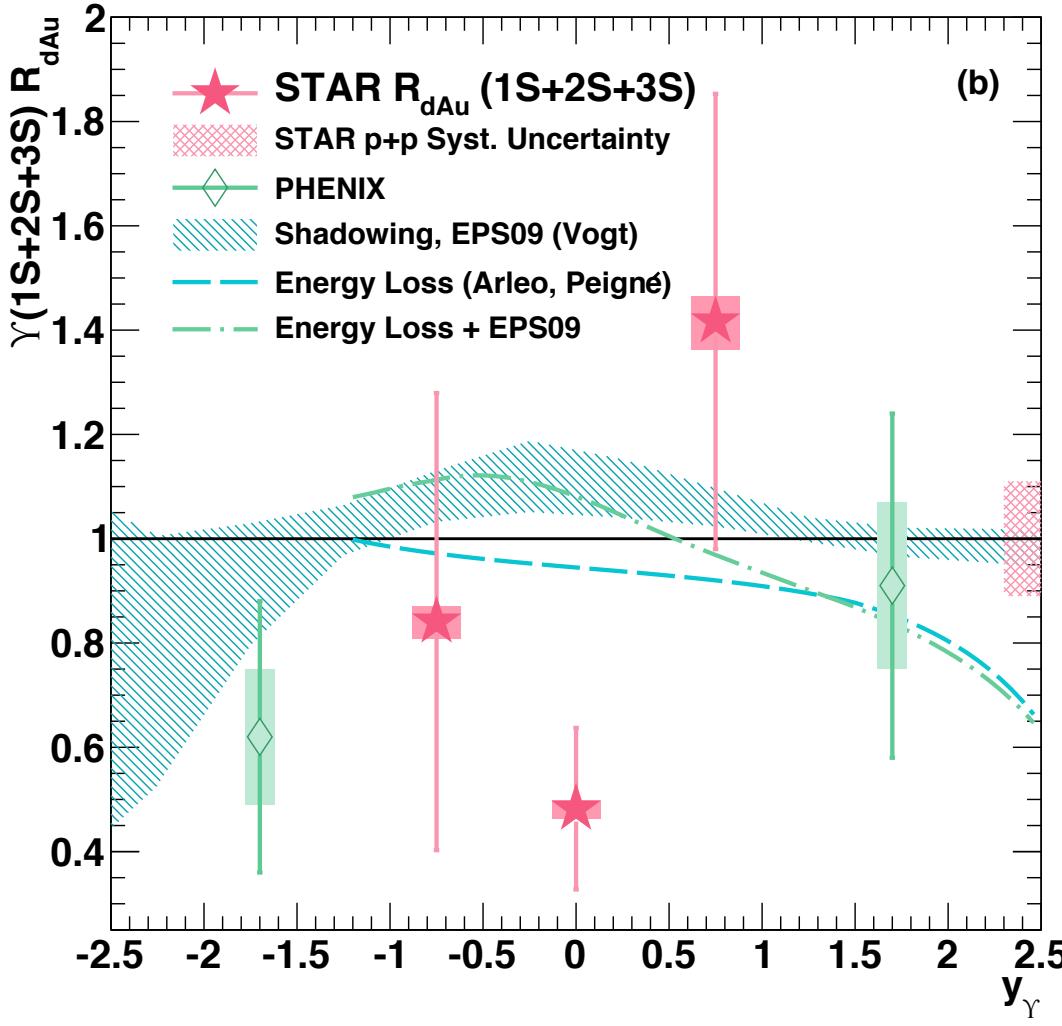
p+p  $\Upsilon$  cross-section vs.  $y$ ,  
compared to pQCD predictions



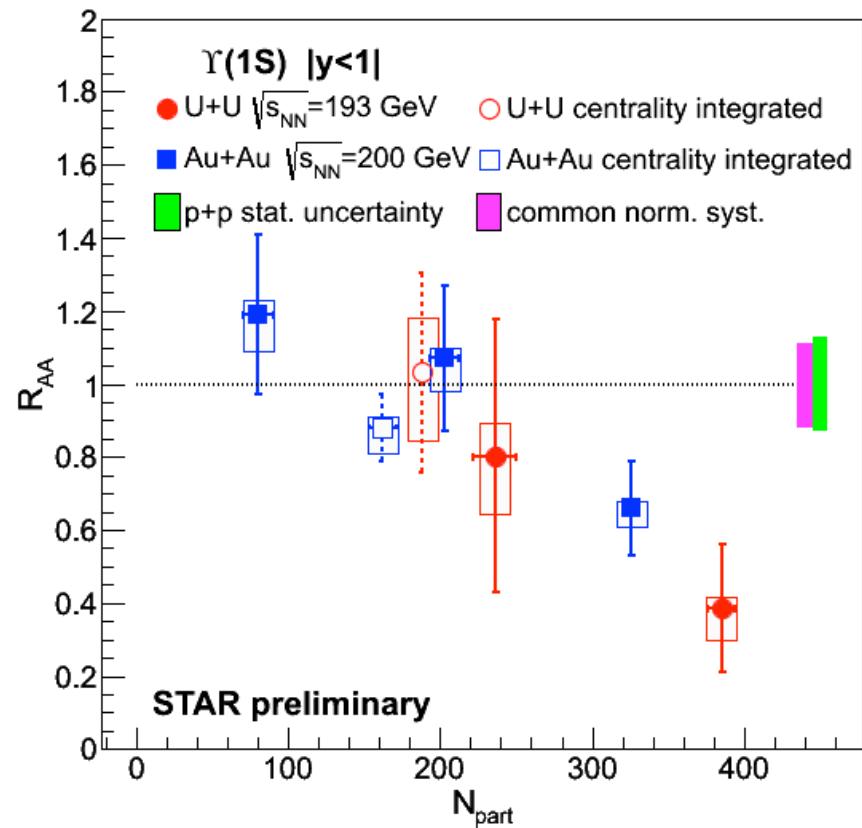
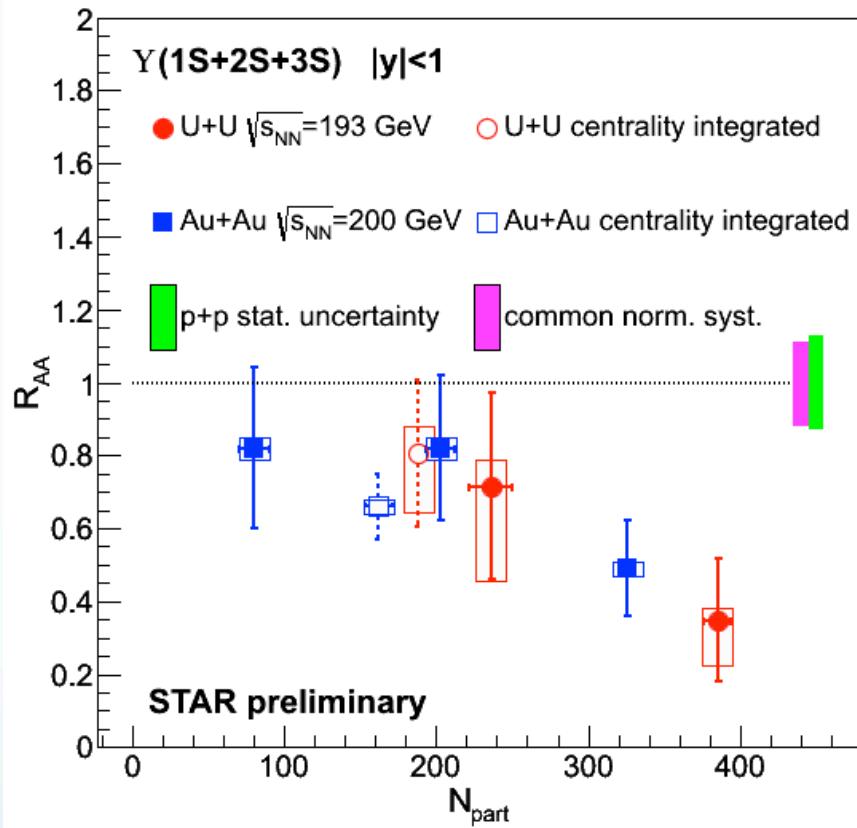
p+p  $\Upsilon$  cross-section, compared  
to world data trend



# $\gamma$ CNM Effects



- Models include
  - Gluon nPDF  
(Anti)shadowing
  - Initial parton energy loss
- Indication of suppression at mid-rapidity beyond model predictions
  - Interpretation of Au+Au results

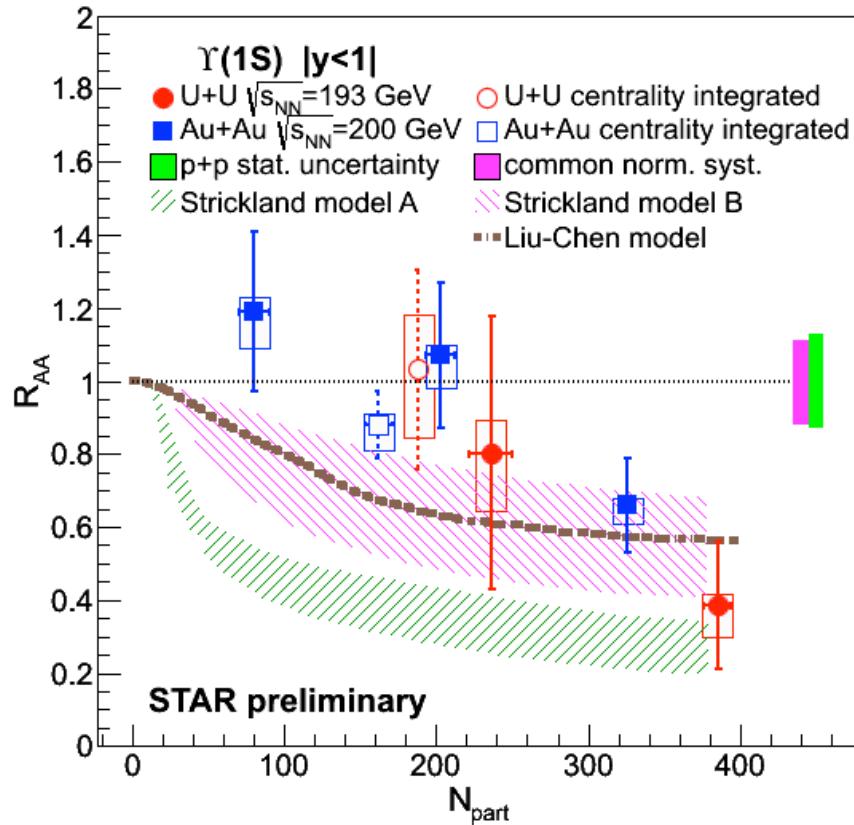
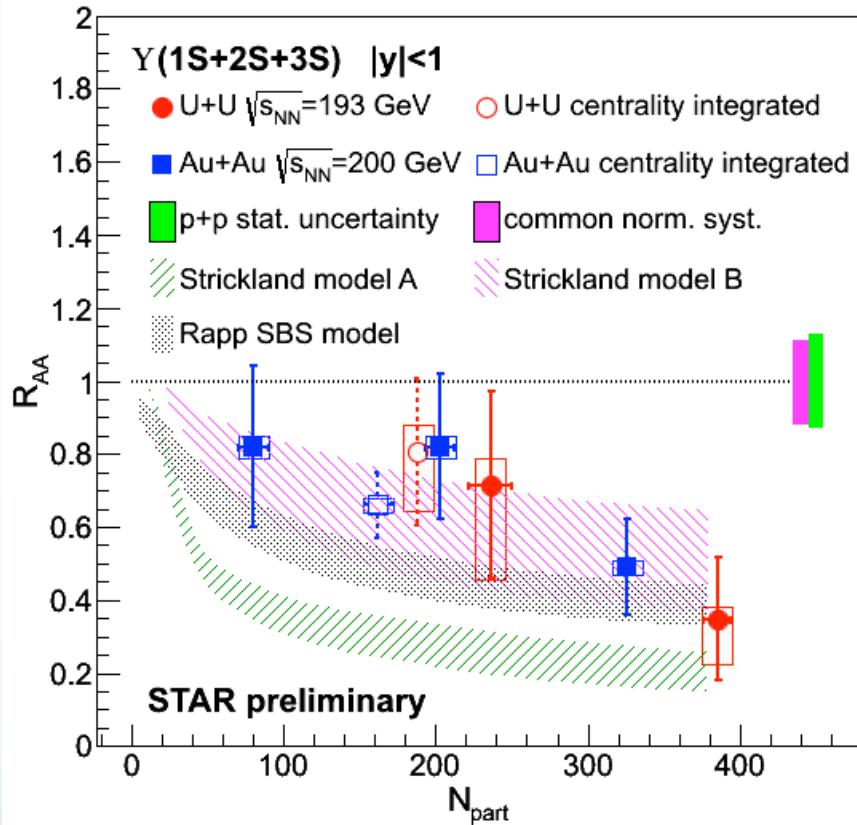


Peripheral  $\gamma$ :  
consistent with no suppression

Central  $\gamma$ :  
significant suppression

Central  $\gamma(1S)$ :  
significant suppression

# $\Upsilon R_{AA}$ : data vs. models



**Strickland, Bazov, Nucl.Phys.A 879, 25 (2012)**

- No CNM effects,  $428 < T < 443$  MeV
- Potential model 'B' based on **heavy quark internal energy**
- Potential model 'A' based on **heavy quark free energy** (disfavored)

Rosi Reed - High pT Workshop

**Liu, Chen, Xu, Zhuang, Phys.Lett.B 697, 32 (2011)**

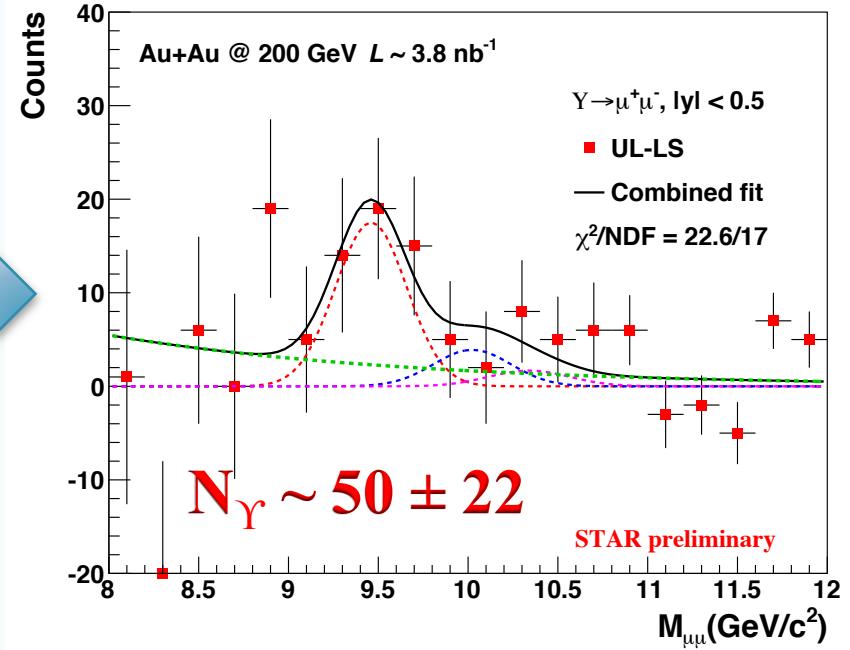
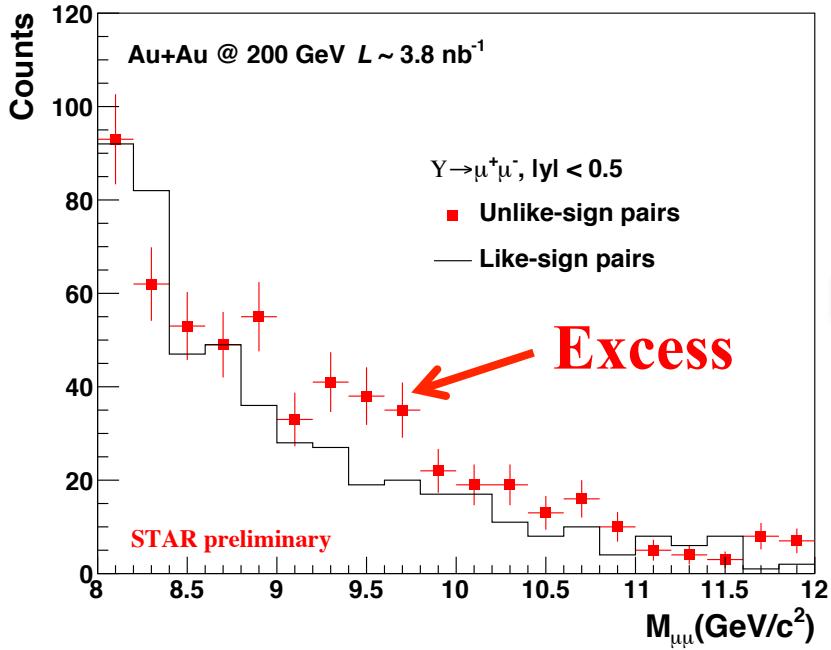
- Potential model, no CNM effects
- $T=340$  MeV, only excited states dissociate

**Emerick, Zhao, Rapp, Eur.Phys.J A48, 72 (2012)**

- **CNM effects** included
- Strong binding scenario

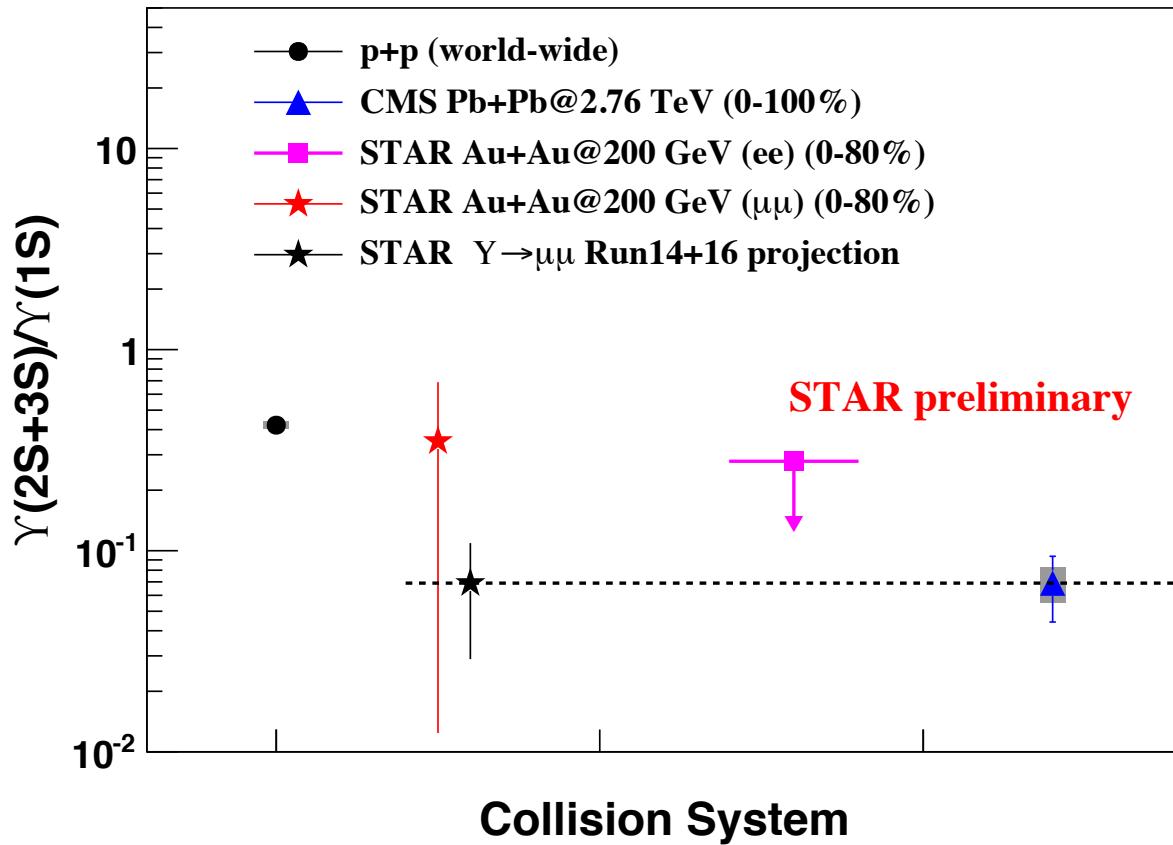


# $\Upsilon \rightarrow \mu^+ + \mu^-$ measurement



- Fit background subtracted distribution to determine yield
  - $\Upsilon$  mean is fixed to PDG value
  - $\Upsilon$  width is determined from simulation.
  - Ratio of  $\Upsilon(2S)/\Upsilon(3S)$  is fixed to pp value
  - Shape of bb and Drell-Yan background is estimated using PYTHIA

# $\Upsilon(2S+3S)/\Upsilon(1S)$ ratio



- Consistent with di-electron channel within large error bars
- The statistical error will be further reduced:
  - A factor of 7x more statistics with full Run 14 + 16 data
  - Mixed-event technique can reduce statistical error by  $\sqrt{2}$

PLB 735 (2014) 127  
PRL 1029(2012) 222301



# Υ Conclusions

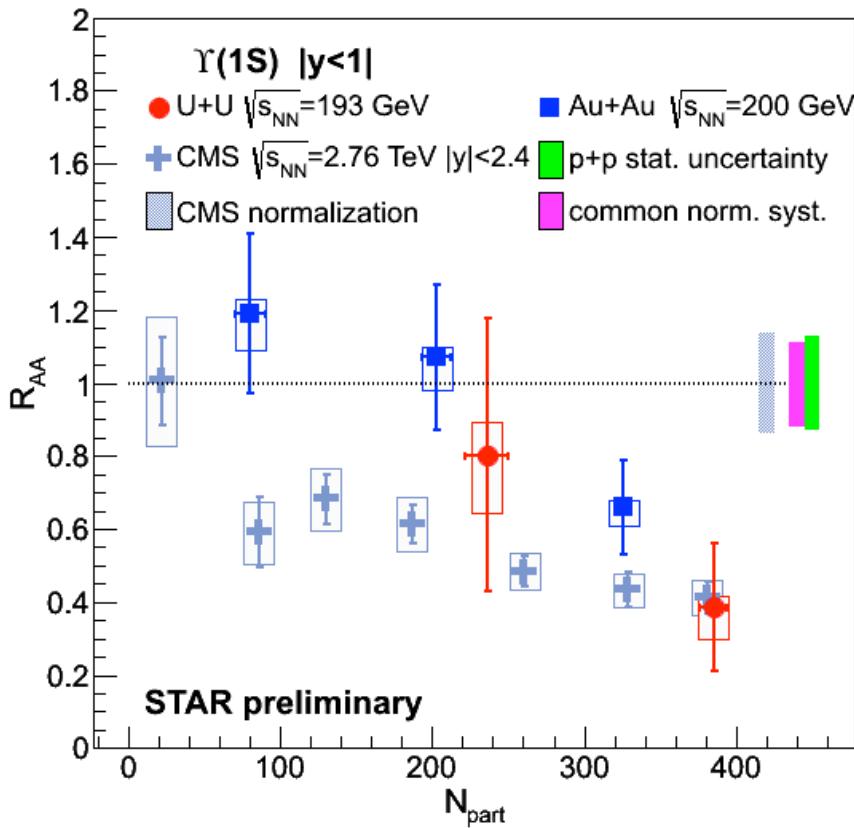
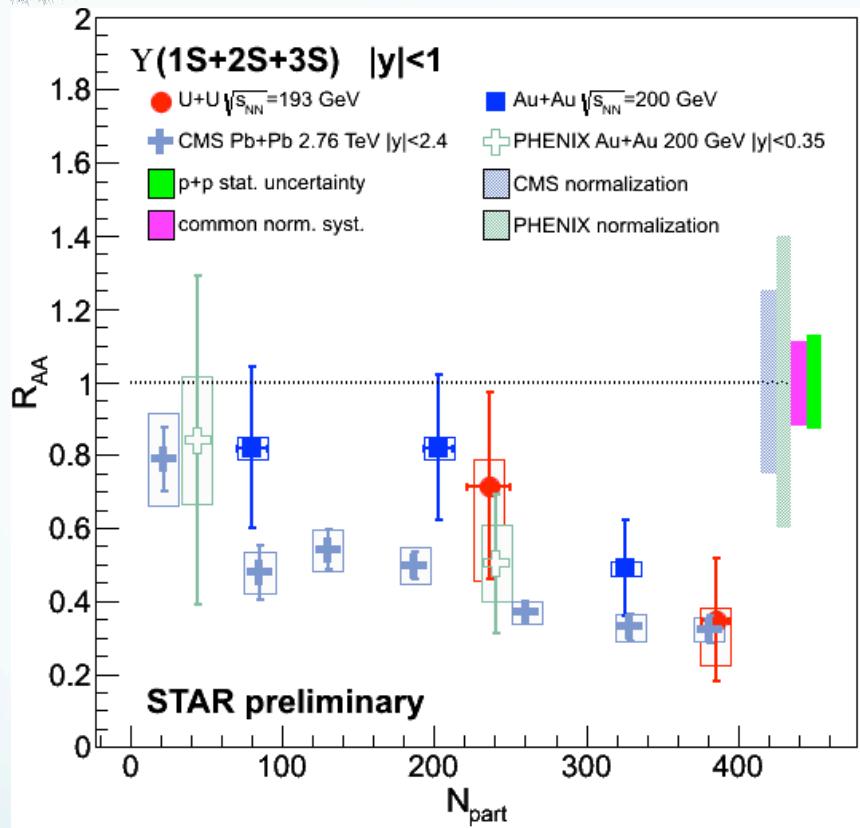
- First quarkonium measurements via di-muon channel at mid-rapidity by the STAR experiment
  - First sign of **Υ signal in di-muon** channel in STAR with a factor of 7x more data expected
- Hot medium effects: Significant suppression of Υ(1S) suppression in central A+A collisions
  - Υ(2S) and Υ(3S) suppression is stronger than Υ(1S)
    - Clear signal of dissociation in a deconfined medium
    - Sequential suppression at 200 GeV!
  - CNM effects: Υ suppression in d+Au has to be understood
  - Similar suppression to high- $p_T$   $J/\psi$



# Back-Up



# STAR $\Upsilon R_{AA}$ : RHIC & LHC comparison



- LHC and RHIC suppressions are comparable at high  $N_{part}$
- $N_{part}$  dependence of  $\Upsilon$  suppression appears weaker at the LHC
- Note the uncertainties and  $y$ -range, however